

Study of Expansive Soil Behavior Using Low to Medium Frequency Electromagnetic Waves

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ABSTRACT

An innovative approach to fully understand expansive soil identification and quantitative movement prediction lies in understanding the *surface phenomena* of individual clay particles within the soil matrix. The impact of incorporating such physicochemical fundamental material properties into unsaturated soil mechanics research will have a transformative influence on foundation design of critical infrastructure. The electrical properties of soil have been shown to be a good indicator of moisture, contamination and mineralogy and are being studied in order to gain a better insight into macroscopic soil behavior. This article will discuss the methodology of the low to medium frequency electromagnetic measurement and the limitations and subsequent solutions found to ensure accurate values of dielectric permittivity (dispersion) to be used in the prediction of expansive soil behavior.

INTRODUCTION

The dielectric permittivity is related to the volumetric water content and is a function of the amount of compaction of the soil and has been used to monitor soil moisture (Selig and Mansukhani 1975), predict porosity (Arulanandan 1991), and determine the presence of contaminants (Thevanayagam 1993) and sulfates (Bredenkamp and Lytton 1994). It has also been shown that in clay minerals, the dielectric permittivity varies as a function of frequency, which is called the dielectric dispersion (Arulanandan and Yogachandran 2000) and can be used to quantify the composition of soils (Arulanandan and Smith, 1973). Low to medium frequency (from several Hz to less than 100MHz) electromagnetic measurements of dielectric real permittivity and effective conductivity have been used by many researchers (Arulanandan and Smith, 1973; Basu and Arulanandan, 1973; Klein and Santamarina, 1997; Ning, 2007) with all involving the usage of a two-terminal electrode system. However, there are several limitations to this kind of test including circuit impedances, electrode dimension and spacing and electrode polarization. This article will discuss and address these limitations in order to achieve more accurate permittivity and conductivity values. It is anticipated that this type of micro-scale dielectric measurement will be combined with traditional geotechnical testing methods to assist in the prediction of macroscopic expansive

soil behavior.

TESTING AND CALIBRATION METHOD OF TWO-TERMINAL ELECTRODE SYSTEM

A HP 4193A vector impedance meter (400kHz-110MHz) was used to perform the electrical measurements. Open circuit, short circuit and standard circuit tests were performed before measuring soil impedance. Open circuit and short circuit tests were done to eliminate the unwanted impedance in series and in parallel with the specimen (Klein and Santamarina, 1997); the standard test was aimed at reducing the measurement sensitivity. A resistor of 1kΩ was used for the standard circuit test. The calibration circuits are given as Figure 1 below.

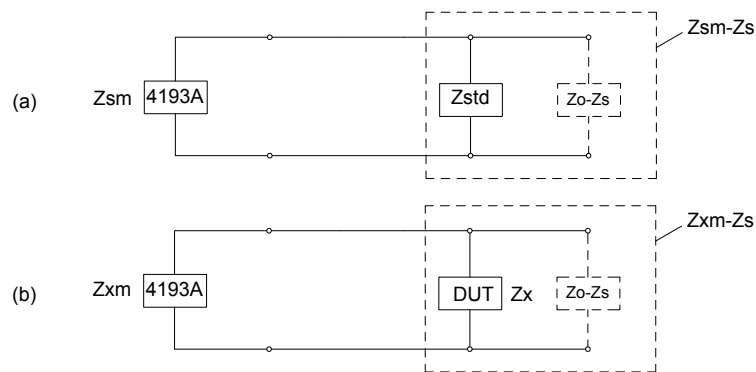


Figure 1. Circuits for testing impedance of (a) standard resistor (noted by Z_{std}) and (b) DUT (device under test, noted by Z_x)

In Figure 1, Z_{sm} and Z_{xm} are impedances of the two circuits; Z_o and Z_s are impedances of open and short circuit measurements, respectively; Z_{std} and Z_x are impedances of a standard resistor with resistance of 1kΩ and device under test (DUT). The impedance of DUT is:

$$Z_x = Z_{std} \cdot \frac{(Z_o - Z_{sm})(Z_{xm} - Z_s)}{(Z_o - Z_{xm})(Z_{sm} - Z_s)} \quad (1)$$

The expressions for real permittivity (denoted as permittivity for the remainder of the article) and effective conductivity (denoted as conductivity) are:

$$\epsilon = \frac{\text{Im}(1/Z_x)}{\omega \epsilon_0 (S/d)} \quad (2)$$

$$\sigma = \frac{\text{Re}(1/Z_x)}{S/d} \quad (3)$$

Where $\epsilon_0 = 8.85 \times 10^{-14}$ farad/cm is the permittivity of vacuum; ω is the circular frequency; d is the length of a specimen and S is the cross sectional area of the electrodes.

THE EFFECT OF ELECTRODE DIMENSION

Differently sized and spaced electrodes affect the resulting dielectric permittivity measurement of a specific soil. In the past, researchers have tested the dielectric permittivity in a fixed cell, with the electrode dimension and spacing unchanged. While the effect of electrode size and spacing was implicitly included in their calibration of their cell, they were limited to manufactured cells and static soil testing. However, in our research, it is required to measure dielectric permittivity over a changing spacing of electrodes (i.e., swelling soil), and therefore it is necessary to determine correction factors to be used for any electrode dimension and spacing. These comprehensive correction factors make it relatively easy for a researcher to use a multitude of electrode sizes and spacing and be confident that the results are comparable for the same soil, as well as allow for data comparisons within the literature. Considering the general dimension of the testing cell, correction factors can be added to Equations (2) and (3), expressed as follows:

$$\epsilon = \frac{\text{Im}(1/Z_x)}{\omega \epsilon_0 (\alpha S/d)} \quad (4)$$

$$\sigma = \frac{\text{Re}(1/Z_x)}{\beta S/d} \quad (5)$$

Thus, it is crucial to know if there is a definite relationship between α , β and the cell constant (S/d). A test setup is designed for this purpose. The setup frame is made of Plexiglas. Four pairs of electrodes with different size and spacing were tested, with copper wires connected to the component adaptor of HP4193A. The sketch of the test setup is given in Figure 2 below.

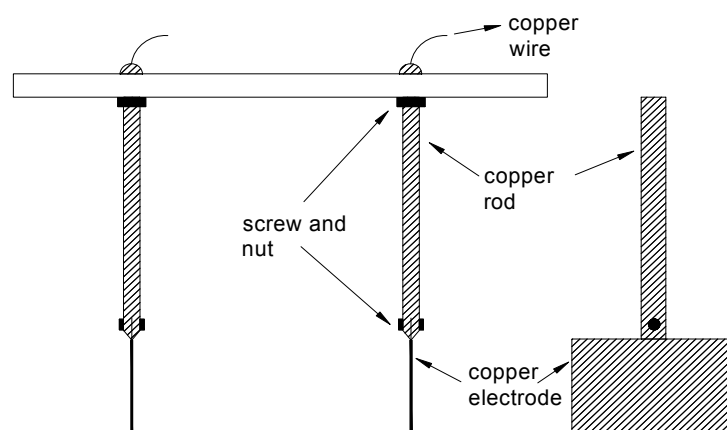


Figure 2. Test setup for measurement of correction factors

Given that the permittivity and conductivity of a single-component homogeneous material do not change according to the low to medium frequency range, de-ionized water ($\epsilon' = 80$ at 25°C) is chosen as the standard liquid for

determining α ; an electrolyte solution with direct current (DC) conductivity $1413\mu\text{S}/\text{cm}$ (at 25°C) is chosen for determining β . The relation curves of $\alpha/(\text{S}/\text{d})$ and $\beta/(\text{S}/\text{d})$ versus cell constant S/d at four frequencies are shown in Figure 3 and Figure 4, respectively. To describe the relationship between correction factors and cell constant, the following two equations are introduced:

$$\alpha/(\text{S}/\text{d})=k_1(\text{S}/\text{d})^{-m_1} \quad (6)$$

$$\beta/(\text{S}/\text{d})=k_2(\text{S}/\text{d})^{-m_2} \quad (7)$$

In which k_1 , k_2 , m_1 and m_2 are parameters that change with frequency. By fitting $\alpha/(\text{S}/\text{d})\sim(\text{S}/\text{d})$ and $\beta/(\text{S}/\text{d})\sim(\text{S}/\text{d})$ curves at each frequency using a power type regression method, these parameters can thus be obtained.

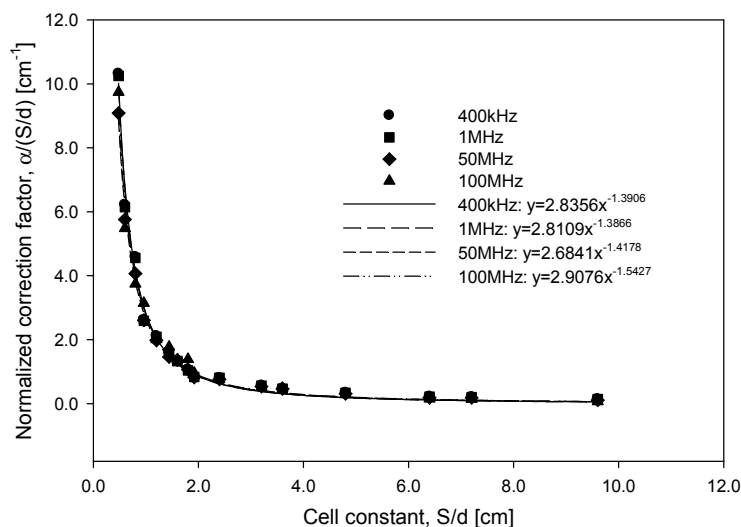


Figure 3. Normalized correction factor α versus cell constant S/d at 400kHz, 1MHz, 50MHz and 100MHz

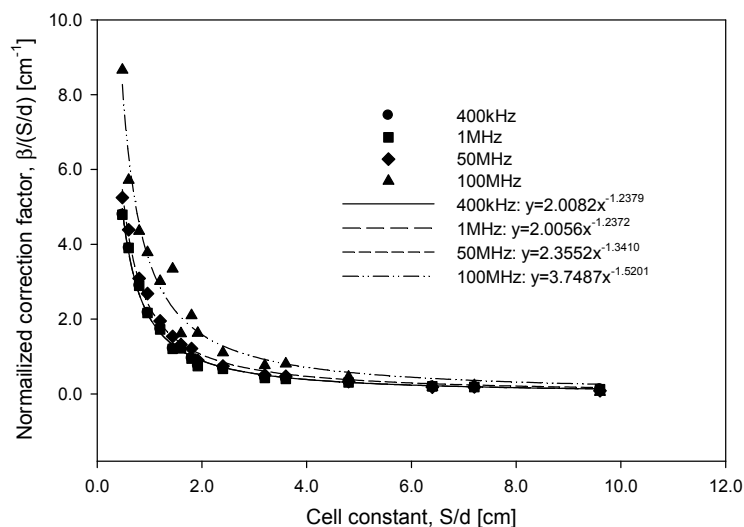


Figure 4. Normalized correction factor β versus cell constant S/d at 400kHz, 1MHz, 50MHz and 100MHz

METHOD FOR CORRECTION OF ELECTRODE POLARIZATION

Because of the ionic nature of current in wet soil and the incompatibility among charges that exist in soil and in electrodes, charge accumulation occurs at the electrode-soil interface, the effect of which is called electrode polarization (Klein and Santamarina, 1997). Electrode polarization exists over a low frequency range up to several MHz. The existing measurement methods to eliminate or minimize the electrode polarization effect are mostly ineffective and unreliable (Santamarina et al. 2001). In this research a constant phase angle (CPA) element (Bao et al. 1992) is attached to the equivalent circuit to represent the effect of electrode polarization. Based on the concept of the CPA element Bardi and Cametti (2001) derived the equations to reduce the effect of electrode polarization as:

$$\varepsilon'_{eq}(\omega) = \frac{\varepsilon' + A\omega^{1-\mu}(\varepsilon'^2 + \varepsilon''^2)\sin(\mu\pi/2)}{1 + A^2\omega^{2(1-\mu)}(\varepsilon'^2 + \varepsilon''^2) + 2A\omega^{1-\mu}(\varepsilon'\sin(\mu\pi/2) + \varepsilon''\cos(\mu\pi/2))} \quad (8)$$

$$\varepsilon''_{eq}(\omega) = \frac{\varepsilon'' + A\omega^{1-\mu}(\varepsilon'^2 + \varepsilon''^2)\cos(\mu\pi/2)}{1 + A^2\omega^{2(1-\mu)}(\varepsilon'^2 + \varepsilon''^2) + 2A\omega^{1-\mu}(\varepsilon'\sin(\mu\pi/2) + \varepsilon''\cos(\mu\pi/2))} \quad (9)$$

Where ε'_{eq} and ε''_{eq} , ε' and ε'' are real and imaginary parts of equivalent circuit and specimen permittivity, respectively; A and μ are fitting constants. A non-linear regression method is used to determine the parameters of the electrode polarization effect according to a chosen relaxation function. Here a quasi-Debye interfacial relaxation function is chosen as:

$$\varepsilon(\omega)^* = \varepsilon'_{\infty} + \frac{\varepsilon'_0 - \varepsilon'_{\infty}}{1 + (i\omega\tau)} - i \frac{\sigma_{dc}}{\omega\varepsilon_0} \quad (10)$$

Where ε'_{∞} and ε'_0 are the real part of the complex permittivity $\varepsilon(\omega)^*$ at the high and low frequency limits, respectively; σ_{dc} is the DC conductivity of the soil-electrolyte mixture and τ is the relaxation time. This function is suitable for describing the predominant relaxation mechanism for mixtures (Santamarina et al., 2001) within the frequency range from 0.1MHz to 1GHz (Ning, 2007).

TESTING OF SOIL SPECIMENS

A modified oedometer was designed at the University of Oklahoma that combines the testing of 1-D soil movement and soil dielectric permittivity. The device is able to control the volumetric water content of the tested soil and the chemical properties of the soil-liquid phase. A sketch of the device is given in Figure 5. Notice that the lateral electrodes are curved and indented inside the Plexiglas ring. As a result, the aforementioned method of obtaining correction factors does not apply to this pair, and a specific group of correction factors were measured for it using the same calibration liquids. Because the spacing and position of this electrode pair are both fixed, the corresponding correction factors do not change because the soil only deforms vertically. The rest of the analysis

follows the procedure discussed in the abovementioned sections.

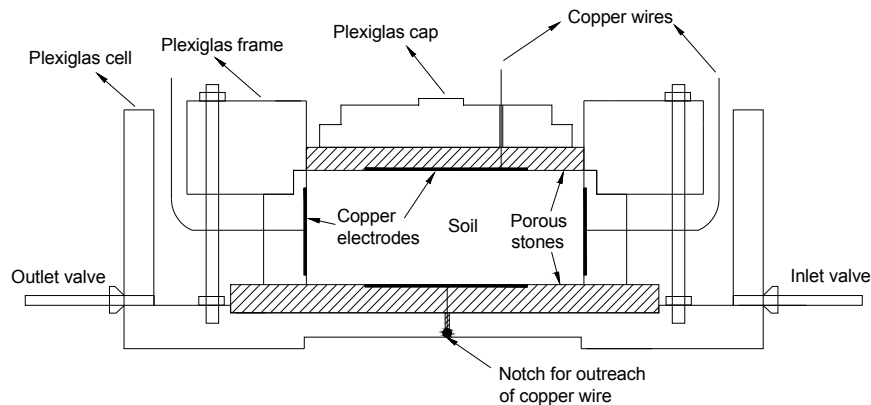


Figure 5. Sketch of the modified oedometer designed for the research

Four soils, silicon flour, kaolinite, sodium bentonite and calcium bentonite were tested at their saturated state, in which the last three were prepared as a slurry. The properties of the soils are listed in Table 1. Klein et.al (2003) mentioned that the effective conductivity data are minimally impacted by electrode polarization effect at kHz frequencies and higher. Moreover, the measurement of conductivity becomes unreliable beyond a frequency of around 23 MHz. As a result, only the permittivity values were recorded and fitted together with the measured data as shown in Figure 6. To study the effect of anisotropy and concentration of the soil liquid phase on permittivity, another two Kaolinite specimens were tested with the result shown in Figure 7.

Table 1. Some physical properties of the soils for the dielectric permittivity tests

Soil type	Total specific surface area (m ² /g)	Liquid limit (%)	Plastic limit (%)	Specific gravity	Cation exchange capacity (meq/100g)
Ca-bentonite [#]	767	130	58	2.81	120.0
Na-bentonite [#]	554	626	60	2.75	40.0
Kaolinite [#]	42	71	32	2.68	2.3
Silicon flour [*]	0.113	-	-	2.65	-

[#] data tested at the University of Oklahoma

^{*} data provided by Prof. Santamarina of Georgia Tech

DISCUSSION

Once a standardized testing method is established for the measurement with low to medium frequency electromagnetic waves, the electrical properties of soils can be correlated to their engineering properties. Moreover, common geotechnical testing methods are able to be modified to accommodate the measurement of electrical properties.

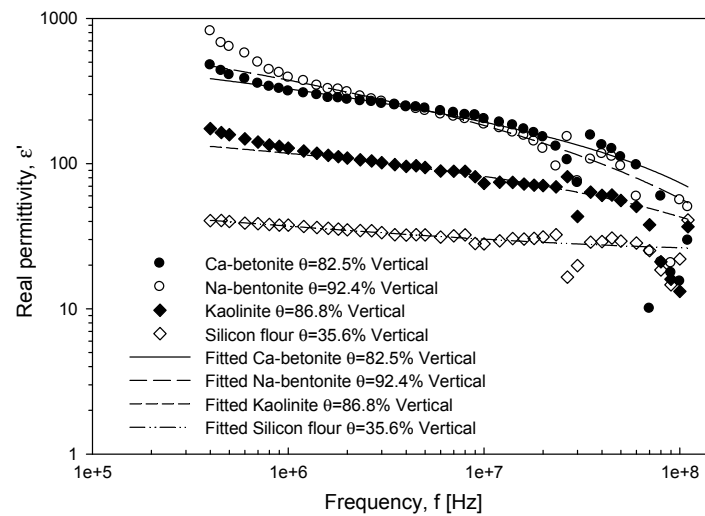


Figure 6. Test data and fitted curves of Ca-bentonite, Na-bentonite and kaolinite at different volumetric water contents tested vertically

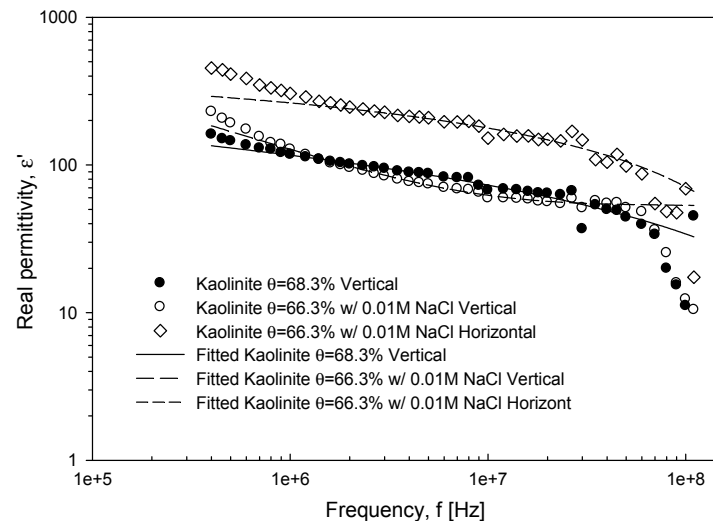


Figure 7. Test data and fitted curves of kaolinite tested with and without mixing with 0.01M NaCl solution

The underlying mechanism of using correction factors originates from the properties of electrode itself and the nature of the electrical field between the parallel electrodes. There are three factors that contribute to such mechanism: smoothness of electrode, electrode induced capacitance and inductance, and fringe effect between two parallel electrodes.

For clays with high specific surface area and high volumetric water content, surface conductance, which is proportional to cation exchange capacity over specific surface area, plays a major role in the determination of soil permittivity (Figure 6). From Figure 7 it is observed that soil anisotropy has an important effect on both permittivity and dispersion; while the concentration of the soil liquid has little impact when it is low. At high volumetric water content, the kaolinite particles tend to lie in parallel to the horizontal direction that make

charges easier to accumulate at the interfaces between soil constituents, which in turns enhances the interfacial polarization and thus increases the measurement of permittivity.

CONCLUSIONS

Three limitations are discussed in reference to soil measurements using low to medium frequency electromagnetic waves. Methods are proposed to solve these problems. Several soil specimens are tested following the proposed methods and the results are reasonable and representative of the specific soil behavior. The research is still on-going and the combination of electrical properties with other microscopic soil properties is expected in order to predict macroscopic behavior of expansive soil in the field.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0746980; Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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